Chapter 8. VLHC Experiments and Detector Issues

The Stage-1 VLHC with 40 TeV and Stage 2 with 175 TeV center of mass energy will, as each stage comes on line, provide the world's highest energy proton proton collisions. Experience with large-scale collider detectors built over the last two decades demonstrates that at these frontier exploration energies general-purpose detectors are best. The major reasons for this choice is space in the collider ring for experiments, their high cost, and the long time scale for construction and operation. As discoveries are made physics priorities will change over the detector lifetime. The number of general-purpose experiments for the VLHC is a compromise between available resources and the need for confirmation of new results and discoveries. We assume that the VLHC will have two general-purpose detectors. These will be designed for Stage 1 and then upgraded or replaced for Stage 2. In this chapter we describe the major experimental parameters for the Stage-1 detectors, then outline the experimental challenges for Stage 2 and conclude with the accelerator detector interface requirements for Stage 1.

8.1 Description of Experiment Parameters for Stage 1

The goal of a general-purpose collider detector is to measure the largest possible number of independent quantities for each trigger event. These include e/μ identification, sign of charge and momentum, detection and measurement of isolated photons, measurement of jet energies and directions, identification of jets with b-hadrons, determination of charged particle multiplicities, and detection of non-interacting neutrals. The major parameters for VLHC detectors have been discussed at Snowmass 1996 [1] and at the 1997 VLHC Physics and Detector Workshop held at Fermilab [2]. The SSC detectors, SDC [3] and GEM [4], were designed to achieve the above stated goals, while operating at a luminosity of 10^{33} $cm^{-2}s^{-1}$. Detectors currently under construction at LHC, CMS [5] and ATLAS [6], are designed for a center of mass energy of 14 TeV and luminosity $10^{34}cm^{-2}s^{-1}$ equal to the Stage-1 VLHC design. Therefore, the major parameters for the VLHC detectors can be based on the large amount of R&D and design work done for the above experiments.

Experimentally detectable objects are charged tracks and clusters of electromagnetic and/or hadronic energy. Detector parameters can be optimized based on a set of benchmark physics processes, e.g. Higgs particle production or the search for supersymmetry. We are looking for the heaviest particles at an energy frontier machine. These are produced almost at rest in the center of mass system and therefore the acceptance for the decay products is basically proportional to the detector solid angle coverage. Based on this assumption rapidity coverage up to ~3 is sufficient for ~90% detection efficiency. An exception to this rule is neutrino detection. In order to reach good missing energy resolution, calorimetry acceptance up to a rapidity of ~5 is needed. For detection of charged tracks we are aiming at good momentum resolution up to the maximum energy of the decay objects. Typically this energy is 5 – 10 % of the center of mass energy; so for a 40 TeV machine we are interested in reconstruction of particles with momentum up to ~ 3 TeV/c.

A hypothetical generic VLHC detector is described beginning from the central region of the detector: the central tracking system. Typically this region consists of two sub-detectors: a precision vertex detector and a tracking system for momentum measurement. Vertex detection is very important. Decay of many heavy objects occurs via decay into massive b quarks. In order to reduce backgrounds from production of light objects (copious at such energies) detection of b quark decay a few mm to cm away from the original vertex is necessary. For precision vertex detectors, silicon detectors are mainly used. Some of them [6] have areas of hundreds of square meters. As the radiation dose in the central rapidity region depends weakly on the colliding beam energy and linearly on luminosity LHC type detectors (with some modifications) could be used for the Stage-1 VLHC. In order to increase radiation hardness and improve coordinate resolution, silicon pixel detectors are under extensive R&D study [7].

Reconstruction of charged particle tracks and their momentum measurement is performed in the tracking system. There are two major goals: pattern recognition in a high multiplicity environment and precision momentum measurement in the TeV region. Different types of gaseous detectors, silicon or scintillation fiber detectors could be used in this region. Momentum resolution about 5 – 10 % could be reached with such technologies for momenta up to ~3 TeV/c and three sigma charge identification up to ~15 TeV/c. For momentum measurements there is a solenoidal magnetic field in the central area of the detector. Typical values for the field are in the range 2 – 4 T. Mechanical forces in the magnet limit this field. The presence of the superconducting solenoidal magnet requires a liquid He supply to the detector area and appropriate cryogenic plant, so special cavern(s) are required close to the experimental halls (see Section 7.5).

Calorimetry is used to measure the energy of electrons, gammas and jets as well as missing energy in the event. As the depth of the hadronic shower (which defines calorimeter thickness) depends logarithmically upon particle energy, the overall size of the calorimeters is similar to SSC and LHC experiments. Calorimeter energy resolution is proportional to 1/v(E) and improves with energy increase up to a constant limit, typically a few percent or less. Therefore calorimetry becomes a precision tool for measurement of event parameters at very high energy. Currently most of the large collider detector calorimeters are liquid Ar or scintillation/Cerenkov light type. As the collision energy increases, heavy gas calorimeters could become efficient and be an inexpensive solution for ionization calorimetry. The radiation dose for the Stage-1 VLHC in the central calorimeter region is manageable, although in the very forward region special radiation hard techniques, like tungsten with quartz fibers, will have to be used.

The muon detection system is located outside the calorimeter. Muon tracks are bent in the muon magnet/absorber, enabling the trigger to select high momentum muons. The muon magnets also improve muon momentum resolution at very high energy and provide track points at large distances from the interaction region. One of the most challenging problems in muon detection in the TeV energy range is that at these energies, muons start to behave like electrons, irradiating electromagnetic debris along their tracks in the absorbers. This debris complicates reconstruction of muon hits, especially at the trigger level and requires multiple hit measurement along the muon track as well as special shielding materials.

An important part of the detector design is the shielding necessary to reduce background. A major source of background is interaction of proton fragments with the beam pipe and other interaction region components. Special shielding design can reduce background flux by orders of magnitude [8], reducing radiation dose to the detector components and improving triggering and track reconstruction capabilities.

One of the major challenges for detector operation at such high luminosity is the large number of interactions per crossing. At a luminosity of 10^{34} $cm^{-2}s^{-1}$ and beam crossing time of 18.8 ns, the average number of interactions per crossing will be 19 (Section 1.3). While most of these events are soft minimum bias events, they complicate central tracker triggering and reconstruction. Calorimetry and muon systems are less affected by high multiplicity events. It is basically impossible to separate events from the same crossing based only on timing information. On the other hand, in order to reduce overlap of events from different crossings, achieving detector and electronics resolution time less than the beam crossing time is at premium. This is especially true at the triggering level where only limited information about the event is available. Ideally charge collection time from the detector should also be less than the beam crossing time.

Radiation flux is another major challenge for the VLHC detectors. Table 8.1 compares the estimated dose at different distances from the beam pipe for one year of running at design luminosity for the Stage-1 VLHC and LHC detectors. In the central rapidity region the dose values are comparable, so detector technologies developed for the LHC detectors could be adopted for the VLHC as well.

Table 8.1. Radiation dose in Mrad per year for LHC and Stage-1 VLHC at 90^0.

	LHC	*VLHC*
Vertex detector (~10 cm)	3	5
Central tracking (~50 cm)	0.25	0.3
EM calorimeter (~150 cm)	0.06	0.1
Hadron calorimeter (~250 cm)	2×10^{-3}	$\sim 3 \times 10^{-3}$

An important part of any experiment is the trigger system. It should reduce the initial interaction rate of about 50 MHz to a manageable rate of about 50 Hz for writing events to tape. With a high occupancy of detector elements and a large number of readout channels a typical event size is in multi Mbyte range. This translates to a Gbyte per second tape rate. It is important to select only interesting classes of events at the trigger level and reduce the huge data sample manipulation after events are written to tape. So, triggering capabilities are an important consideration in detector design and special fast trigger electronics need to be developed.

A general detector design based on the above considerations is shown in Figure 8.1. This concept is well established and proven based on the Fermilab and CERN collider experiments.

One of VLHC design parameters is the size of the detector cavern. This will be mainly determined by the muon system. For high precision muon momentum resolution, the required size of the hall is large. Table 8.2 shows hall sizes together with muon momentum resolution. Based on these numbers and taking into account the evolution of the detectors from Stage-1 to Stage-2, the experimental caverns should have a length of about 60 m and diameter of about 30 m plus additional space for personnel and equipment access (Section 7.5).

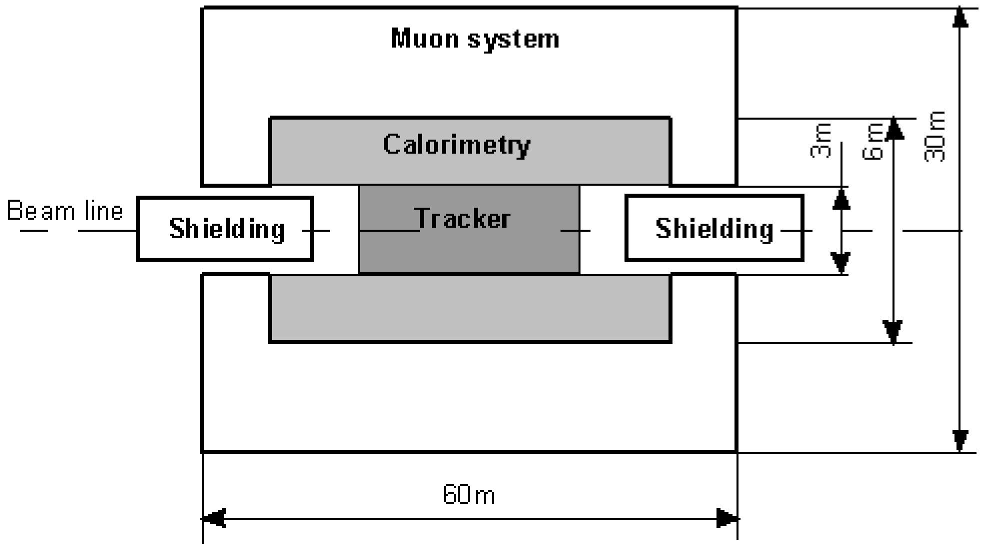

Figure 8.1. Layout of a general purpose VLHC detector.

Table 8.2. Hall sizes and momentum resolution at momentum of 1 TeV/c.

Experiment	*Hall size, m^3*	*dp/p, %*
SDC (SSC)	29 × 29 × 50	11
GEM (SSC)	24 × 24 × 76	10
CMS (CERN)	26 × 26 × 60	5
ATLAS (CERN)	25 × 25 × 53	8

Today's detector technology provides a wide selection of choices for the Stage-1 VLHC detectors. Experience obtained in designing SSC and LHC detectors is very important. ATLAS and CMS designs could be used for Stage-1 VLHC with minor modifications. In order to reduce detector cost and improve operational parameters, detector R&D is important. For each of the detector subsystems R&D studies should concentrate on providing high radiation tolerance, resolution time below 19 ns beam crossing time, high segmentation as well as reliable long term operation and low construction and operational costs. Development of very fast electronics to digitize signals from detectors, select events with interesting topology with an input rate of 50 MHz should be part of the R&D program as well.

8.2 Description of Major Experimental Challenges for Stage 2

The upgrade from Stage-1 to Stage-2 will increase the luminosity a factor of two and the center of mass energy nearly a factor of four. These increases in energy and luminosity provide a significant increase in the collider physics reach [2], but bring major challenges to detect and reconstruct events. In this section we will discuss how the increase in energy and luminosity will affect detectors.

From 40 to 175 TeV, both the charged track multiplicity and the inelastic cross section increase [9], and the luminosity is twice as large. As a result, the radiation dose in the central region is a factor of ~3 higher than in Stage-1. Figure 8.2 shows the energy flux per unit of rapidity for 100 TeV center of mass. Most of the energy is deposited in the forward region. Dose in the calorimeter located at a rapidity of ~5 will be about 1 Trad per year, a serious experimental challenge.

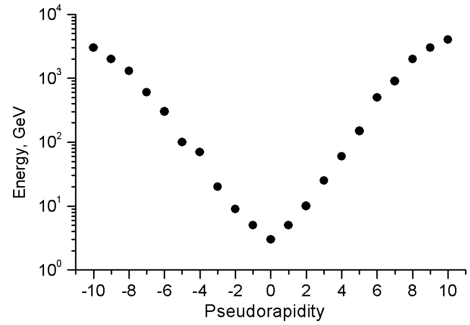

Figure 8.2. Calculated energy flux per unit of rapidity for pp collisions at energy 100 TeV.

The average number of minimum bias interactions per crossing for Stage 2 will be about 49, a factor of three increase from Stage 1. This large number of interactions per crossing creates pile up of events in the tracking detectors as well as in the calorimeter. Figure 8.3 shows the energy deposition in a calorimeter cone, $(\Delta\phi^2 + \Delta\eta^2)^{1/2}$ of 0.4 in the central rapidity region for 1000 overlapped events at an energy of 100 TeV. At a luminosity of 2×10^{34} cm^{-2}s^{-1} the average energy deposition in a 0.4 cone will be about 350 GeV. This "pedestal" level will fluctuate due to statistical fluctuation in the number of events per crossing as well as with changes in luminosity. While challenging this task is similar to operation of calorimeters at LHC where the energy flux will be about factor of ~5 lower. Muon system pile up of events is less important, as the probability to a have high-energy muon in a minimum bias event is ~10^{-5}.

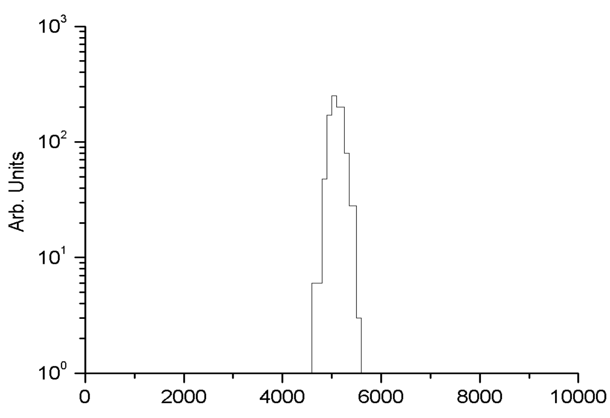

Figure 8.3. Energy deposition in a cone 0.4 for 10^3 overlapped events at 100 TeV center of mass energy.

With increase in energy the detectable decay products will have higher energy as well. Calorimetry energy resolution is improving as 1/v(E) and will be limited by the constant term and pile up fluctuations. The real challenge will be momentum measurement of the charged particles and muons. If the energy of the detectable objects we are looking for increases proportional to the center of mass energy we will need momentum resolution of about 10% for 5 – 10 TeV particles. Presently designed detectors at 10 TeV (see Table 8.2) will have 50% resolution at best. So, improvements in charged particle detection (precision of tracking detectors, value of magnetic field, and/or size of the lever arm) are needed. Another approach is to think about detectors based mainly on calorimeter information.

In summary, Stage 2 of the VLHC will be similar to Stage 1 in terms of occupancies and radiation dose in the central region as luminosity, inelastic cross section, and charged particle multiplicities each increase by a small factor. Calorimetry will become very precise with resolution limited by event pile up and the energy resolution constant term, while charged particle momentum measurements in the region 1 – 10 TeV will require serious design and R&D efforts.

8.3 Machine-Detector Interface Requirements for Stage 1

There is a set of accelerator and detector interface parameters, important for efficient detector operation. The most important of these are: the dimensions of the beam interaction region, beam abort due to abnormal losses, location of the low beta quads, shielding from background from collisions in accelerator components and background from the accelerator tunnel.

The beam interaction region is described in two planes: perpendicular to the beam pipe and along the beam direction. For triggering on displaced vertices and missing energy it is preferable to keep the beam diameter below 50 μm. It is also important to maintain beam center location stable to within 1 mm during the store and locate the beam to within a few mm with respect to the beam pipe center. Usually these requirements are easily met. The size of the interaction region along the beam pipe is not as well defined. A smaller interaction region has advantages and disadvantages. Advantages are better missing E_t resolution and smaller detector size. Disadvantages are overlap of events in the tracking detector, and more difficult pattern recognition in the muon and calorimeter systems. Usually the compromise length is $\sigma \sim 30$ cm, which means that 99% of events occur in a region ± 1 m around the detector center.

Some of the detector elements are sensitive to radiation, especially those elements of the tracking system located close to the beam pipe. In order to prevent excess irradiation of these components during unexpected high loss a feedback loop to the accelerator control room will be provided. If the integrated dose or the irradiation rate increase above specific levels the beam will be aborted to prevent damage to the detector. Such systems exist at all hadron colliders and are well developed.

The requirement of hermetic calorimetry to measure missing energy sets the calorimeter pseudorapidity coverage at about ± 5 [5,6]. In order to locate calorimeters close enough to the beam pipe as well as provide space for access to the detector elements the low beta quads should be located at a distance of about 20 m from the center of the interaction. A more specific number for this parameter will be determined from specific detector design.

There are two major sources of background hits in the muon detectors which are difficult to reduce: (1) sprays from hadronic and electromagnetic showers developed along detector cracks and along the beam pipe from accelerator components and (2) backgrounds coming from the tunnel produced by beam losses along accelerator. Cracks between sub-detectors will be minimized. Nevertheless there will be background from these cracks and originating from the collision point. This background will be reduced with a tapered beam pipe as well as shielding along the beam pipe. There is considerable experience in designing such shielding [3,4,5,6,8]. Reduction in charged particle flux up to two orders of magnitude, especially in the muon detectors, can be achieved.

In order to define an acceptable background flux of particles from the tunnel, this flux has to be compared with backgrounds coming from the interaction region, taking into account the effect of shielding. Typical measured/estimated background flux on the muon detectors from the interaction region is $(0.1 – 1) \times 10^6$ $\text{particles} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ [5,10]. The flux of particles from the tunnel should be below this number. In the case of the CDF and D0 experiments, 2 m of thick concrete shielding in the tunnel on both sides of the detector was needed in order to reduce background to an acceptable level. Results of MARS [11] calculations of the background flux in the Tevatron agree well with observations, so as soon as the interaction region lattice and beam parameters are known, backgrounds can be calculated and ways explored for reducing them.

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